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THE OVERPRESSURE-DURATION RELATIONSHIP AND LETHALITY IN SMALL ANIMALS

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FOREWORD

This report deals with research in the field of blast and shock biology. It presents the results of experiments in which four small-animal species were exposed to air blasts in the short-duration range that were generated with different weights of high-explosive charges. The data were combined with previous shock-tube information to define the tolerance of small animals to sharp-rising overpressures as a function of duration.

The results are limited to small animals and to sharply rising, single-pulse, air-blast waves of the ideal type. They do not apply to other pressure-time patterns. The findings are applicable to military and industrial situations involving potential exposure to air blast.

This study is part of a broad program: one segment of which is to establish interspecies correlation between animal size and tolerance to air blast as a function of pulse duration to aid extrapolations applicable to the human case.

ABSTRACT

A total of 993 mice, rats, guinea pigs and rabbits were exposed to sharp-rising overpressures of various short durations. They were mounted on a concrete pad above which high-explosive charges, ranging in weight from 0.50 oz to 64 lbs, were detonated.

Pressure-time measurements were obtained with pencil-type and shock-tube piezo-electric gauges on the pad directly beneath the charges. The duration of the blast waves ranged from 0.40 msec to 6.8 msec. The LD_{50} pressures were calculated for each species at the different pulse durations.

In general, the pressures required to produce 50-percent lethality rose at the shorter durations. Combining the results of this study with those from previous shock-tube investigations made it possible to define the tolerance of four small-animal species to sharply rising overpressures as a function of pulse duration.

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INTRODUCTION

The magnitude of the overpressure from an air blast required to produce animal injury and death depends on the duration of the overpressure (the time the pressures remain above atmospheric) and the character of the leading edge of the pressure wave; that is, whether the pressure rises in a single shock, multiple shocks or a gradual, smooth manner[1-5].

In general, for sharp-rising pressures associated with a single pulse, animals' tolerance to pressure falls off rather markedly with increasing durations[2]. Fortunately, there is a trend for animals' resistance to sharp-rising air blasts of a given duration to be directly related to species size. Advantage has been taken of this relationship to predict human tolerance through interspecies correlations of the mortality data obtained with five and six species of experimental animals[3,4]. However, the predicted values for human tolerance can only apply to the pressure durations employed in gathering the experimental data. For instance, with sharp-rising pressures of 2-to 3-msec duration, man's tolerance, in terms of overpressure required to produce 50-percent lethality (LD_{50}), was calculated to be between 370 and 470 psi[3]. In contrast, when lethality data, compiled with a 400-msec pulse, were extrapolated to man, an LD_{50} of near 50 psi was obtained[4]. Obviously, there is a need for data on the response of animals to overpressure as a function of duration.

These studies were therefore undertaken to determine the tolerance of mice, rats, guinea pigs and rabbits to high-explosive air blasts of different durations. The results, when added to those from previous shock-tube investigations[4,5,6], would establish the pressure-duration relationship and lethality for those small-animal species.

The gross pathological findings recorded at autopsy will be presented in a separate report.

METHODS

General

In these experiments, animals were exposed to sharply rising overpressures of different durations by mounting them on a concrete pad above which high-explosive charges of various weights were detonated. Pressure-time measurements were made on each test with piezo-electric gauges located at the surface of the pad directly beneath the charge. The mean barometric pressure at the blast range was 12.0 psi.

The Blast Range

The general layout of the blast site appears in Figure 1. It consisted of a 30 x 30-ft pad made of 6-in.-thick reinforced concrete. The explosive charges were suspended above the pad by a cable-pulley system slung between two wooden poles that were located on the east and west sides of the pad.

Embedded in the concrete pad were five rectangular boxes made of 0.5-in steel plate. The inside dimensions of each box were 6 x 12 in. and 6 in. deep. The lids of the boxes served as mounts for the pressure transducers. These lids were removable and were flush with the surface of the concrete pad. The boxes were located so that pressure gauges could be placed at the center of the pad and/or at 2-, 3-, 4- and 8-ft ranges.

Within the concrete pad, 1.5-in. conduit served to carry the wire leads from the pressure gauges to an underground instrumentation bunker that was located about 45 ft from the center of the concrete pad.

High Explosives Utilized

Table 1 gives the information pertinent to the types and number of explosives employed in these experiments. The weights of charges were 64, 8, 1 and 0.25 lbs and 0.50 oz. All charges were spheres, except the 1-lb charge which was in the form of a rectangular block. It was always oriented with its long axis parallel with the surface of the pad. The 64-, 8- and 1-lb charges were composed of TNT, whereas the 0.25-lb explosives were Composition B and the 0.50-oz charges were RDX.

All explosives were fired electrically with the detonator at the center of the charge.

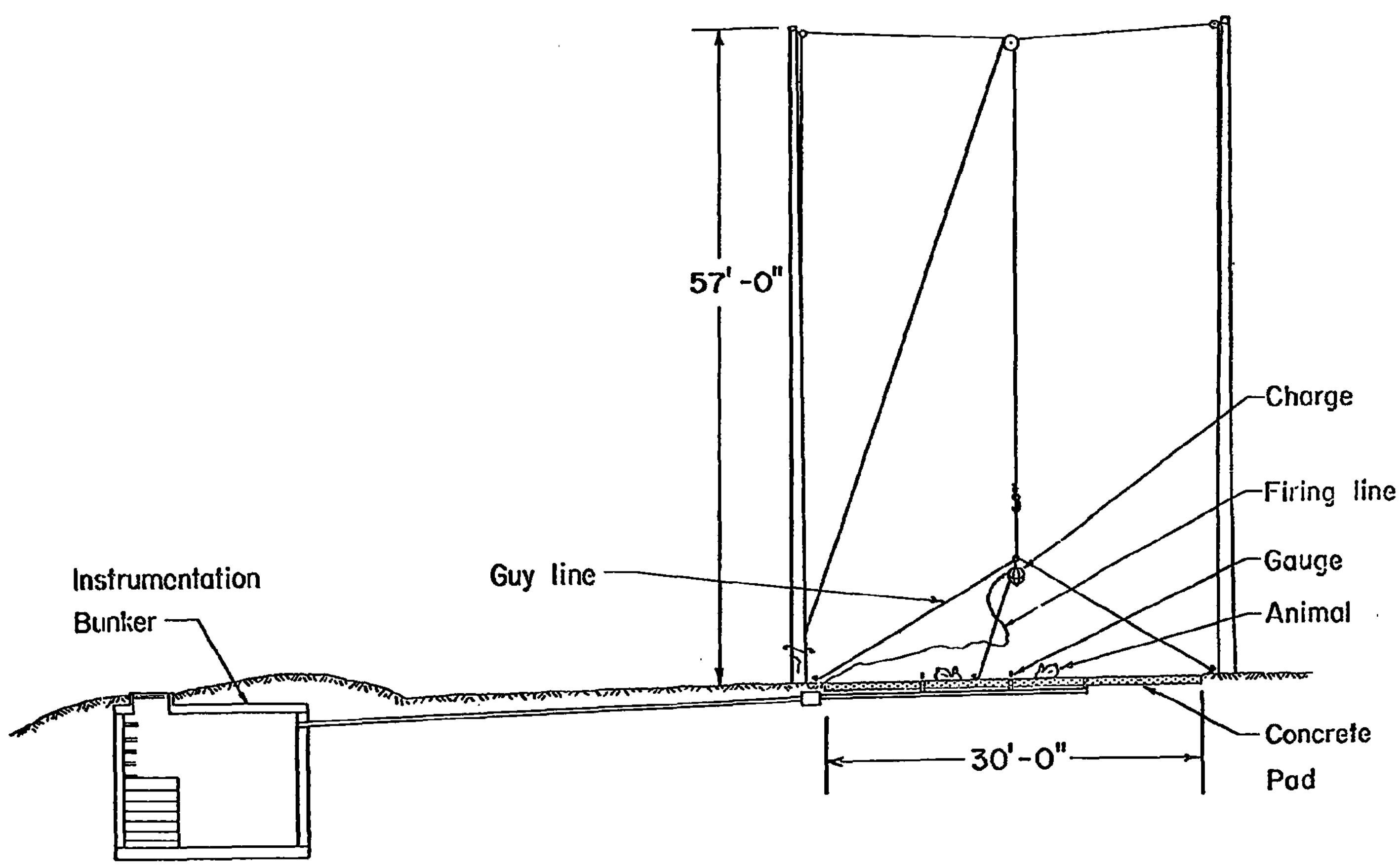
57'-0"
Charge
Firing line
Gauge
Animal
Guy line
Instrumentation
Bunker
Concrete
Pad
30'-0"

Figure 1

TABLE 1

HIGH-EXPLOSIVE CHARGES EMPLOYED IN THIS STUDY

Weight of Charge	Type of Charge	Dimensions of Charges*	Type of Booster	Number Utilized
64 lb	TNT (cast)	13 in. dia. sphere	2 oz-9404PBX	3
8 lb	TNT (cast)	6.5 in. dia. sphere	2 oz-9404PBX	17
1 lb	TNT (pressed)	7x7/8x1-7/8 in. Rectangular Block	none	42
0.25 lb	Composition B	2 in. dia. sphere	none	36
0.50 oz	RDX	1 in. dia. sphere	none	87
			Total	185

*Detonated with Herco-Tube® electric blasting caps (Hercules Powder Co.).

Experimental Animals

Table 2 gives the number of animals from each species that were exposed to the blast from the different weights of charges detonated at various heights above the pad. The height was measured from the center of the explosive to the surface of the pad.

A total of 993 animals was utilized, of which 414 were mice (23.8 gm mean body weight), 218 were rats (200 gm), 197 were guinea pigs (547 gm) and 164 were rabbits (1.9 kg). All animals were exposed to the air blast in a prone position on the concrete pad. With the exception of 20 guinea pigs mounted in cages (described below), all animals were held in place by nylon strings connected to their legs by metal clamps.

Animals Directly Beneath the Explosive Charge

All animals, except 110 mice, were exposed directly beneath the charge. The circular area beneath the charge in which the animals were placed was well within the region in which the regular reflection of the incident shock front could be expected to occur. In addition, according to calculations, the magnitude of the reflected pressure should not decay more than 10 percent over the distance of the circle's radius. The diameter of the circles, as a function of the scaled height of burst for the five weights of charges, is plotted in Figure 2. Consequently, the number of animals tested on each shot depended upon the height and weight of the explosive employed.

Caged Animals

To determine the protection afforded by an animal cage, 20 guinea pigs were exposed to the air blast in single cages – 10 each on two of the 8-lb shots. They were paired with 20 non-caged guinea pigs. The cages were identical to those used in previous shock-tube studies with guinea pigs[4,5,6]–measuring 3 x 3 x 8-1/2 in. and made of expanded metal which provided approximately 60 percent open area.

Animals to the Side of the Charge

In order to expose mice to a blast wave having a duration shorter than that recorded directly beneath the smallest charge available (0.50 oz), it was necessary to use a different geometry of exposure. The 0.50-oz charge was suspended 6 in. above the surface

TABLE 2

THE NUMBER OF ANIMALS EXPOSED WITH THE CHARGES AT VARIOUS HEIGHTS

Height of Explosives, ft	Mouse	Rat	Guinea Pig	Rabbit
64-lb TNT:				
30.0	--	--	--	8
28.0	--	--	--	28
Total				36
8-lb TNT:				
15	--	--	42	--
14	--	40	50*	50
13	--	--	10	20
Total		40	102	70
1-lb TNT:				
8.5	40	--	--	--
8.0	60	--	--	--
7.5	20	10	20	--
7.25	--	--	10	--
7.0	--	20	30	--
6.75	--	20	--	--
6.5	--	30	--	22
6.25	--	--	--	4
6.0	--	--	--	17
5.5	--	--	--	6
Total	120	80	60	49
0.25-lb Comp. B:				
5.0	30	--	--	--
4.5	10	--	--	--
4.25	10	25	--	--
4.0	--	35	20	--
3.75	--	--	15	--
3.5	--	--	--	1
3.42	--	--	--	2
3.3	--	--	--	6
Total	50	60	35	9
0.50-oz RDX:				
2.33	40	--	--	--
2.17	94	--	--	--
1.58	--	38	--	--
Total	134	38		
0.50-oz RDX:				
0.50	46	(20 in. to the side)		
0.50	48	(21 in. to the side)		
0.50	16	(23 in. to the side)		
Total	110			
Grand Totals	414	218	197	164

* 20 were in cages.

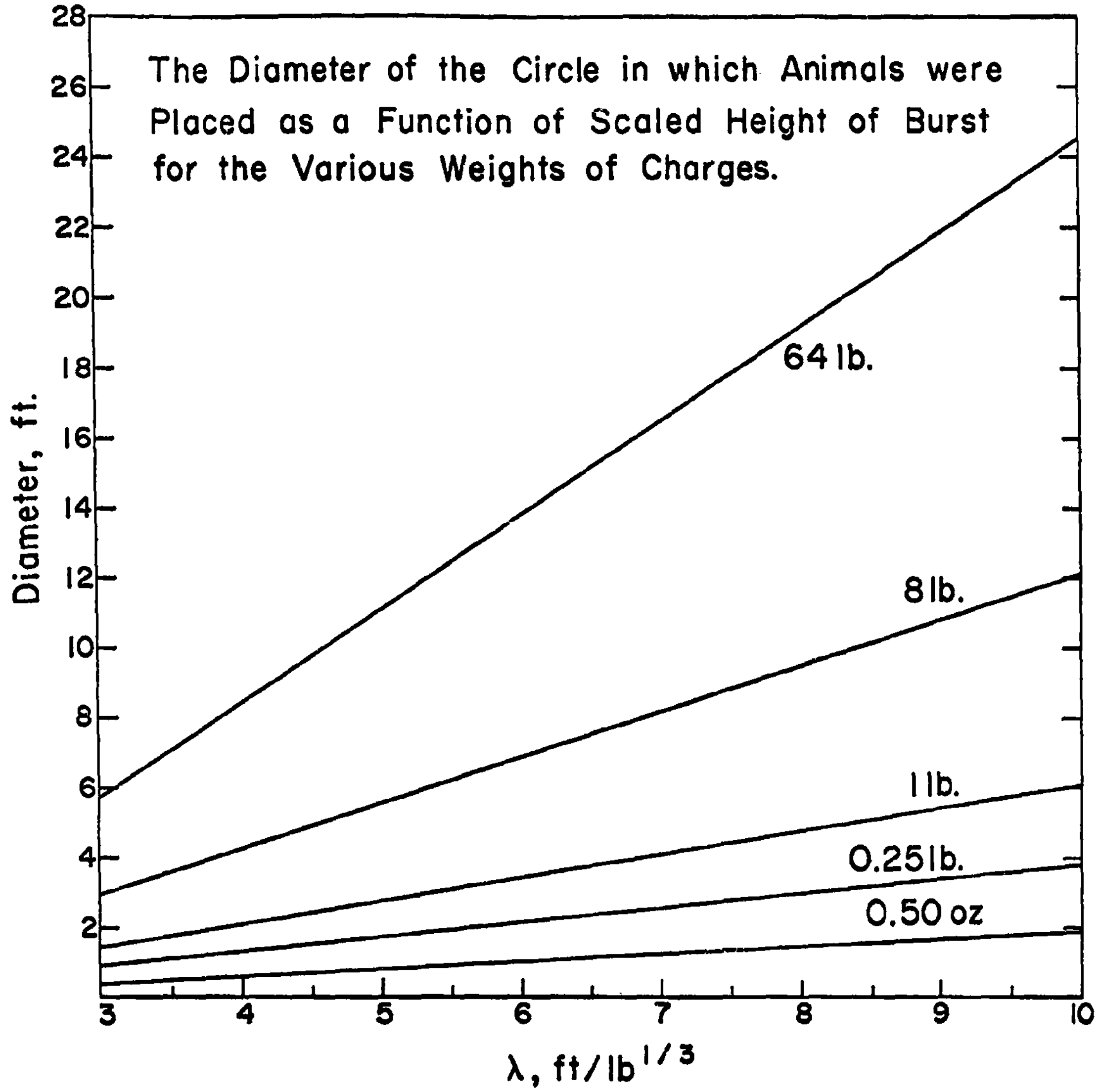
The Diameter of the Circle in which Animals were Placed as a Function of Scaled Height of Burst for the Various Weights of Charges.
64 lb.
8 lb.
1 lb.
0.25 lb.
0.50 oz
Diameter, ft.
28
26
24
22
20
18
16
14
12
10
8
6
4
2
3
4
5
6
7
8
9
10
λ, ft/lb^1/3

Figure 2

of the pad, and the mice were located along the circumference of a circle at ground ranges of 20, 21 or 23 in. from the center of the charge.

Pressure-Time Measurements

Pressure Transducers

Two types of piezo-electric pressure transducers were used to measure pressure-time in these experiments. Pencil-type pressure transducers (Model LC-33, Atlantic Research Corp., Alexandria, Va.) were routinely employed on every test, and were supplemented by a shock-tube gauge (ST-2, Susquehanna Instruments, Bel Air, Md.) in the latter parts of the study — especially those experiments in which the mice were exposed to the side of the 0.50-oz charge.

The pencil-type gauges measured 10 in. in length and were 0.63 in. in diameter. The sensing element was a Lead Zirconate crystal which was located approximately 3 in. aft of the tip of the gauge. The frequency response of the gauge is flat ± 2 db from 1 cps to 80 kcps, having a range from 0 - 500 psi; and it measured the pressure side-on.

Pencil gauges were mounted through holes in the lids of steel boxes. They were shock-mounted and secured to the underside of the lids with just the forward portion of the gauge protruding above the pad. The sensing element of the gauge was therefore always 0.75 in. above the surface of the lid.

ST-2 gauges contained sensors of Lead Metaniobate. They were cylindrical in shape and 0.50 in. in diameter with a frequency response of 200 kcps. They were always placed with the sensing surface flush with the surface of the box lid. The wire leads of the gauges were passed from the inside of the boxes through the conduits into the underground bunker.

Signals from the gauges were fed through Atlantic Type 104-A amplifiers that have high-input impedance (500 meg ohms) and low-output impedance. The amplifiers were powered by an Atlantic Type 105 power supply and have a 1- or 10-times amplification factor. From the amplifiers, the signals were fed into a Tektronix cathode-ray oscilloscope, Type 531-A — modification 104 — having a Type B wide-band, plug-in type preamplifier unit. The trace on the cathode tube of the oscilloscope was photographed by a Beattie-Coleman camera, which had a Polaroid Land camera back-mounted in a periscope assembly.

Sweeps on the oscilloscopes were externally triggered by a signal from a Barium Titanate piezo-electric gauge mounted on a probe about 6 in. above the pad.

Calibration of Pressure Transducers

An air-driven, closed-end shock tube 1-ft in diameter was employed to calibrate the pencil-type gauges. The latter were mounted in the plate that closed the end of the expansion chamber. The sensing elements of the gauges were 3.5 in. from the upstream surface of the plate at calibration. The voltage output of each gauge as a function of the applied shock pressures was determined. Pressures in the shock tube were monitored by Kistler Quartz piezo-electric gauges (Kistler Instrument Corp., North Tonawanda, N. Y.) and from shock-velocity measurements taken with a Hewlett-Packard counter which was started and stopped by the signal from gauges spaced 18 in. apart in the wall of the shock tube. Kistler transducers were statically calibrated, using a small tank in which the pressure was measured by a Heise Bourdon Tube Gauge.* There was good agreement between the magnitude of the shock pressures measured by the Kistler gauges and those calculated from shock-velocity measurements.

The ST-2 gauges were also calibrated on the shock tube in a manner similar to the pencil gauges, except that they were mounted in the wall of the tube.

The amplifier, cables and other fittings associated with a particular gauge at calibration were transferred as a unit to the pad facility. The time-constant and frequency response of the gauges and associated electronic system described above were found adequate to follow the pulse from the blast since it reproduced a pressure wave of a known shape in the calibration shock tube.

Pressure-Time Records

Representative pressure-time records taken with pencil gauges located directly beneath three different weights of explosives are illustrated in Figure 3. Since the sensing elements of the gauges were 3/4 in. above the surface of the pad, the ascending portion of the pressure wave can be resolved into the incident and reflected shock fronts. In the area directly beneath the charge, the incident shock front and the associated flow travel directly toward the pad, whereas the reflected shock travels in the opposite direction — up from the surface of the pad. Consequently, little tethering is necessary to hold animals in place during the blast with this geometry of exposure.

The duration of the overpressure was measured on the pressure-time record between the initial rise of pressure associated with the incident shock front and the point where the trace first crossed below the base line at which time the pressure was at ambient. As noted on some of the pressure records in Figure 3, there is a second small shock near the tail of the pulse. This was not included in the duration of the pressure if it occurred after the pressure first crossed over into the negative phase.

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*Certified by Heise Bourdon Tube Co., Newton, Conn. as calibrated using a master Bureau of Standards piston gauge.

PRESSURE - TIME RECORDS

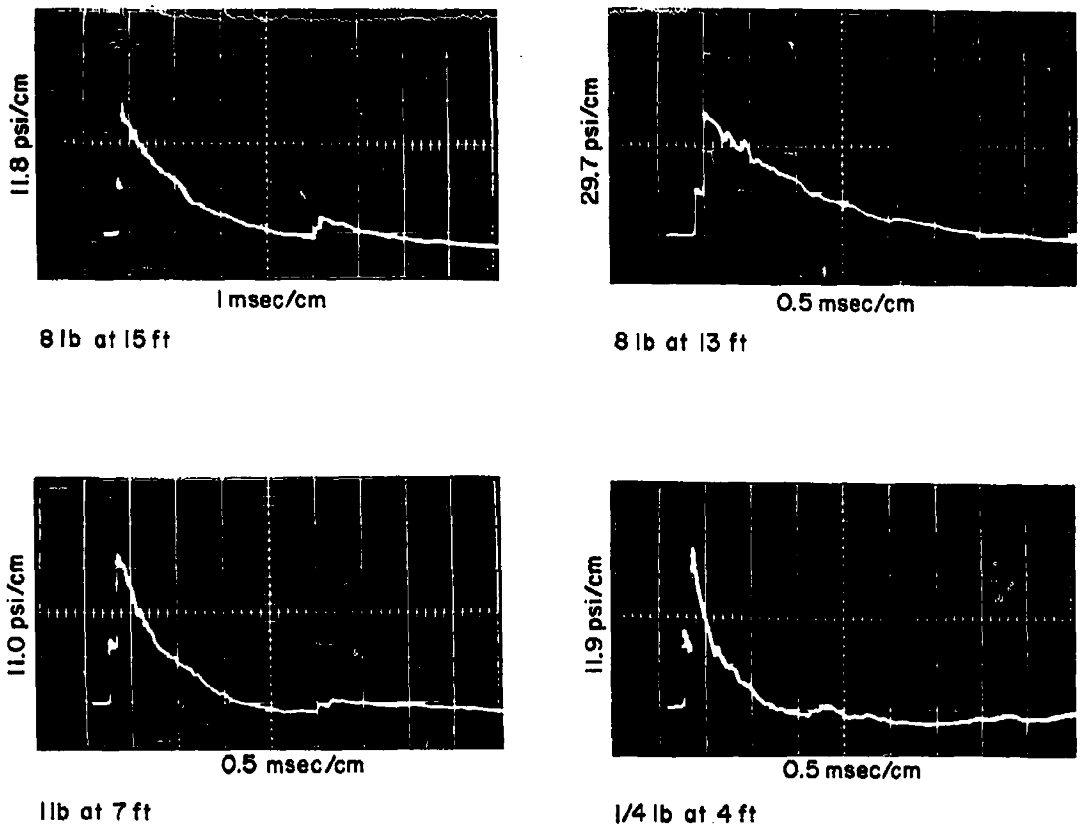


Figure 3

RESULTS

Mortality

The mortality and pressure-time parameters associated with each weight of explosive charge are given in Tables 3 through 6 for mice, rats, guinea pigs and rabbits, respectively. The pressure-time data were taken from gauges located directly beneath the charge – excepting those recorded with mice exposed off to the side of the 0.50-oz charge (Table 3).

By and large, there was an inverse relationship between the peak pressure on the pad and the height of the explosive charge. In some cases, the data obtained with a given weight of charge at slightly different heights were grouped because the pressures overlapped. In a few instances, e.g., the mouse and rat on the 0.50-oz trials (Tables 3 and 4), the pressures obtained with the charges at a given height varied enough that it was possible to divide them into separate groups with their corresponding mortalities.

As noted in Tables 3 through 6, the durations of the pressures grew with the increased weight of explosive. Also, in general and to a far lesser extent, the duration of the pulse from a given weight of charge increased slightly with its distance above the pad. In only one instance (rabbit and 1-lb charge), was this latter variation in duration considered significant; and it was necessary to divide the data into two groups: those of 1.4 msec and those of 1.0-to 1.2-msec durations (Table 6).

The probit analysis[7], programmed for a Bendix G-15 Electronic Computer, was the method used to calculate the LD_{50} pressures (the pressure required to kill 50 percent in a stated period of time). The probit analysis related the percentage mortality in probit units to the logarithm of the reflected shock pressure. The probit method transformed the typical sigmoid mortality curve into a straight line and provided the regression line equation:

$$y = a + b \log x$$

where: y = the percent mortality in probit units
x = pressure, psi
a = intercept constant
b = slope constant

The reader will recall that the mice exposed off to the side of the 0.50-oz charge were subjected to only the incident shock. Consequently, the incident shock pressure was correlated with lethality (Table 3).

TABLE 3

MOUSE MORTALITY AND PRESSURE-TIME DATA OBTAINED WITH EACH WEIGHT OF CHARGE

Height of Charge, ft	Overpressure, psi: Incident Shock	Overpressure, psi: Reflected Shock	Duration, msec	1-hour Mortality: No. Dead / Total	1-hour Mortality: Percent	24-hour Mortality: No. Dead / Total	24-hour Mortality: Percent
0.50-oz RDX (charge to the side of animals):							
0.5	30.4	--	0.42	2/16	12.5	2/16	12.5
0.5	38.4	--	0.38	16/30	53.3	16/30	53.3
0.5	43.4	--	0.41	17/28	60.7	17/28	60.7
0.5	46.2	--	0.43	10/18	55.6	10/18	55.6
0.5	48.9	--	0.40	16/18	88.9	16/18	88.9
			mean 0.41	LD_{50}=39.6		LD_{50}=39.6	
0.50-oz RDX:							
2.17&2.33	13.4	27.7	0.63	7/32	21.9	7/32	21.9
2.17&2.33	15.7	32.9	0.57	23/48	47.9	26/48	54.2
2.17	17.5	37.9	0.47	26/34	76.5	27/34	79.4
2.17	18.5	41.8	0.50	17/20	85.0	17/20	85.0
			mean 0.55	LD_{50}=33.0		LD_{50}=32.4	
0.25-lb Comp. B:							
5.0	12.0	27.4	1.3	3/10	30.0	3/10	30.0
5.0	13.1	30.0	1.4	10/20	50.0	10/20	50.0
4.25&4.5	16.7	39.2	1.2	19/20	95.0	19/20	95.0
			mean 1.3	LD_{50}=29.9		LD_{50}=29.9	
1-lb TNT:							
8.5	8.8	21.0	2.2	1/20	5.0	1/20	5.0
8.5	10.6	24.0	2.1	4/20	20.0	4/20	20.0
8.0	11.5	27.3	2.1	34/60	56.7	38/60	63.3
7.5	12.2	28.5	2.0	17/20	85.0	18/20	90.0
			mean 2.1	LD_{50}=26.0		LD_{50}=26.0	

TABLE 4

RAT MORTALITY AND PRESSURE-TIME DATA
OBTAINED WITH EACH WEIGHT OF CHARGE

Height of Charge, ft	Overpressure, psi Incident Shock	Overpressure, psi Reflected Shock	Duration, msec	1-hour Mortality No. Dead Total	1-hour Mortality Percent	24-hour Mortality No. Dead Total	24-hour Mortality Percent
0.50-oz RDX:							
1.58	27.8	53.1	0.40	1/13	7.7	3/13	23.1
1.58	32.6	65.8	0.40	4/12	33.3	5/12	41.7
1.58	37.7	74.1	0.40	6/13	46.2	8/13	61.5
			mean 0.40	LD_{50}=75.0		LD_{50}=68.5	
0.25-lb Comp. B:							
4.25	16.4	39.4	1.05	2/20	10.0	3/20	15.0
4.0&4.25	17.6	44.0	1.04	5/20	25.0	7/20	35.0
4.0	18.3	46.6	1.03	5/10	50.0	5/10	50.0
4.0	20.1	48.5	1.00	6/10	60.0	7/10	70.0
			mean 1.04	LD_{50}=47.2		LD_{50}=46.0	
1-lb TNT:							
7.0&7.5	14.3	34.2	1.6	0/20	0	3/20	15.0
6.5, 6.75 & 7.0	17.1	42.5	1.6	14/30	46.7	19/30	63.3
6.5&6.75	20.9	52.7	1.5	26/30	86.7	26/30	86.7
			mean 1.6	LD_{50}=44.1		LD_{50}=40.9	
8-lb TNT:							
14.0	12.6	33.2	3.6	4/20	20.0	4/20	20.0
14.0	14.4	37.6	3.6	8/10	80.0	8/10	80.0
14.0	14.4	38.0	3.6	7/10	70.0	7/10	70.0
			mean 3.6	LD_{50}=35.7		LD_{50}=35.7	

TABLE 5

GUINEA PIG MORTALITY AND PRESSURE-TIME DATA
OBTAINED WITH EACH WEIGHT OF CHARGE

Height of Charge, ft	Overpressure, psi Incident Shock	Overpressure, psi Reflected Shock	Duration, msec	1-hour Mortality No. Dead Total	1-hour Mortality Percent	24-hour Mortality No. Dead Total	24-hour Mortality Percent
0.25-lb Comp. B:							
4.0	18.8	45.6	0.85	3/12	25.0	3/12	25.0
4.0	20.0	47.8	0.85	3/8	38.0	4/8	50.0
3.75	24.7	58.8	0.85	12/15	80.0	13/15	86.7
		mean	0.85	LD_{50}=50.9		LD_{50}=49.4	
1-lb TNT:							
7.5	12.2	29.1	1.6	0/10	0	0/10	0
7.5	14.0	34.8	1.6	1/10	10.0	1/10	10.0
7.0	16.0	39.8	1.5	30/40	75.0	30/40	75.0
		mean	1.6	LD_{50}=38.0		LD_{50}=38.0	
8-lb TNT:							
15.0	11.0	28.5	4.2	4/10	40.0	4/10	40.0
15.0	11.0	33.5	3.8	16/32	50.0	17/32	53.1
14.0	14.2	34.1	3.5	16/20	80.0	17/20	85.0
13.0&14.0	13.8	36.0	3.6	18/20	90.0	18/20	90.0
		mean	3.8	LD_{50}=31.2		LD_{50}=31.0	

TABLE 6

RABBIT MORTALITY AND PRESSURE-TIME DATA OBTAINED WITH EACH WEIGHT OF CHARGE

Height of Charge, ft	Overpressure, psi Incident Shock	Overpressure, psi Reflected Shock	Duration, msec	1-hour Mortality No. Dead / Total	1-hour Mortality Percent	24-hour Mortality No. Dead / Total	24-hour Mortality Percent
0.25-lb Comp B:							
3.3, 3.42 & 3.5	26.1	63.9	0.90	3/9	33.3	3/9	33.3
				LD_{50}=67.2*		LD_{50}=67.2*	
1-lb TNT:							
6.0	24.1	64.4	1.2	1/4	25.0	2/4	50.0
6.0	25.0	70.0	1.2	3/4	75.0	3/4	75.0
5.5&6.0	28.0	77.6	1.0	9/10	90.0	9/10	90.0
		mean	1.1	LD_{50}=67.6		LD_{50}=64.1	
1-lb TNT:							
6.5	19.2	50.9	1.4	6/14	42.8	6/14	42.8
6.5	20.4	55.0	1.4	4/8	50.0	4/8	50.0
6.0&6.25	24.8	62.5	1.4	8/9	88.9	8/9	88.9
		mean	1.4	LD_{50}=53.0		LD_{50}=53.0	
8-lb TNT:							
14.0	12.4	32.2	3.6	1/10	10.0	1/10	10.0
14.0	12.8	34.3	3.6	2/10	20.0	2/10	20.0
13.0&14.0	14.3	37.6	3.6	17/40	42.5	18/40	45.0
13.0	16.0	40.4	3.4	7/10	70.0	7/10	70.0
		mean	3.6	LD_{50}=38.3		LD_{50}=38.1	
64-lb TNT:							
30.0	11.8	29.3	-	0/8	0	0/8	0
28.0	13.8	35.5	6.8	4/8	50.0	4/8	50.0
28.0	13.2	36.3	6.8	13/20	65.0	16/20	80.0
		mean	6.8	LD_{50}=35.5		LD_{50}=35.5	

* Computed from 1 data-point (see text).

These LD_{50} values were included beneath the appropriate mortality columns of Tables 3 through 6. In most instances, there was little or no difference between lethality at 1 hour and 24 hours; consequently, only the 24-hour mortality will be referred to throughout the remainder of this report.

The probit mortality curves computed from the 24-hour mortality data obtained with the pressure durations associated with each weight of charge were given in Figures 4 through 7 for the mouse, rat, guinea pig and rabbit, respectively. According to statistical tests, the probit mortality curves for the mice could be considered parallel — as were those for the rats, guinea pigs and rabbits. The adjusted slope constants (b) for the mouse, rat, guinea pig and rabbit equations were 11.953, 11.684, 18.222 and 19.625, respectively.

The LD_{50} for the mouse at durations of 2.1 msec (1-lb charge), 1.3 msec (0.25-lb charge), 0.55 msec (0.50-oz charge) and 0.41 msec (0.50-oz charge) were 26.0, 29.9, 32.4 and 39.6 psi, respectively (Table 3 and Figure 4).

The rat LD_{50} values were computed to be 35.7 psi (3.6 msec), 40.9 psi (1.6 msec), 46.0 psi (1.04 msec) and 68.5 psi (0.40 msec) compiled from the 8-, 1- and 0.25-lb and 0.50-oz detonations, respectively (Table 4 and Figure 5).

With overpressure durations of 3.8, 1.6 and 0.85 msec associated with the 8-, 1- and 0.25-lb charges, LD_{50} pressures for guinea pigs were calculated to be in the same order: 31.0, 38.0 and 49.4 psi (Table 5 and Figure 6).

The mean, lethal reflected pressures for rabbits were found to be 35.5 psi at 6.8-msec duration, 38.1 psi at 3.6 msec, 53.0 psi at 1.4 msec and 64.1 psi at 1.1 msec. The weights of explosives were 64, 8, 1 and 1 lbs, respectively (Table 6 and Figure 7).

As noted in Table 6, only nine rabbits were exposed to the blast from the 0.25-lb charge. It was therefore necessary to calculate an LD_{50} from just one data point: 33.3 percent lethality with a pressure of 63.9 psi. This involved substituting these values into the probit regression line equation along with an average slope constant and solving for the intercept a. This provided a probit regression line equation from which the LD_{50} was computed. The procedure was as follows:

$$y = a + b \log x$$

where: $y = 4.568$ (33.3-percent mortality)

$\log x = \log 63.9$ psi

$b = 19.625$ (the adjusted slope constant computed from the other four regression line equations for rabbits)

$$a = 4.658 - 19.625 \times 1.806$$

$$a = -30.864$$

These LD_{50} values were included beneath the appropriate mortality columns of Tables 3 through 6. In most instances, there was little or no difference between lethality at 1 hour and 24 hours; consequently, only the 24-hour mortality will be referred to throughout the remainder of this report.

The probit mortality curves computed from the 24-hour mortality data obtained with the pressure durations associated with each weight of charge were given in Figures 4 through 7 for the mouse, rat, guinea pig and rabbit, respectively. According to statistical tests, the probit mortality curves for the mice could be considered parallel — as were those for the rats, guinea pigs and rabbits. The adjusted slope constants (b) for the mouse, rat, guinea pig and rabbit equations were 11.953, 11.684, 18.222 and 19.625, respectively.

The LD_{50} for the mouse at durations of 2.1 msec (1-lb charge), 1.3 msec (0.25-lb charge), 0.55 msec (0.50-oz charge) and 0.41 msec (0.50-oz charge) were 26.0, 29.9, 32.4 and 39.6 psi, respectively (Table 3 and Figure 4).

The rat LD_{50} values were computed to be 35.7 psi (3.6 msec), 40.9 psi (1.6 msec), 46.0 psi (1.04 msec) and 68.5 psi (0.40 msec) compiled from the 8-, 1- and 0.25-lb and 0.50-oz detonations, respectively (Table 4 and Figure 5).

With overpressure durations of 3.8, 1.6 and 0.85 msec associated with the 8-, 1- and 0.25-lb charges, LD_{50} pressures for guinea pigs were calculated to be in the same order: 31.0, 38.0 and 49.4 psi (Table 5 and Figure 6).

The mean, lethal reflected pressures for rabbits were found to be 35.5 psi at 6.8-msec duration, 38.1 psi at 3.6 msec, 53.0 psi at 1.4 msec and 64.1 psi at 1.1 msec. The weights of explosives were 64, 8, 1 and 1 lbs, respectively (Table 6 and Figure 7).

As noted in Table 6, only nine rabbits were exposed to the blast from the 0.25-lb charge. It was therefore necessary to calculate an LD_{50} from just one data point: 33.3 percent lethality with a pressure of 63.9 psi. This involved substituting these values into the probit regression line equation along with an average slope constant and solving for the intercept a. This provided a probit regression line equation from which the LD_{50} was computed. The procedure was as follows:

$y = a + b \log x$

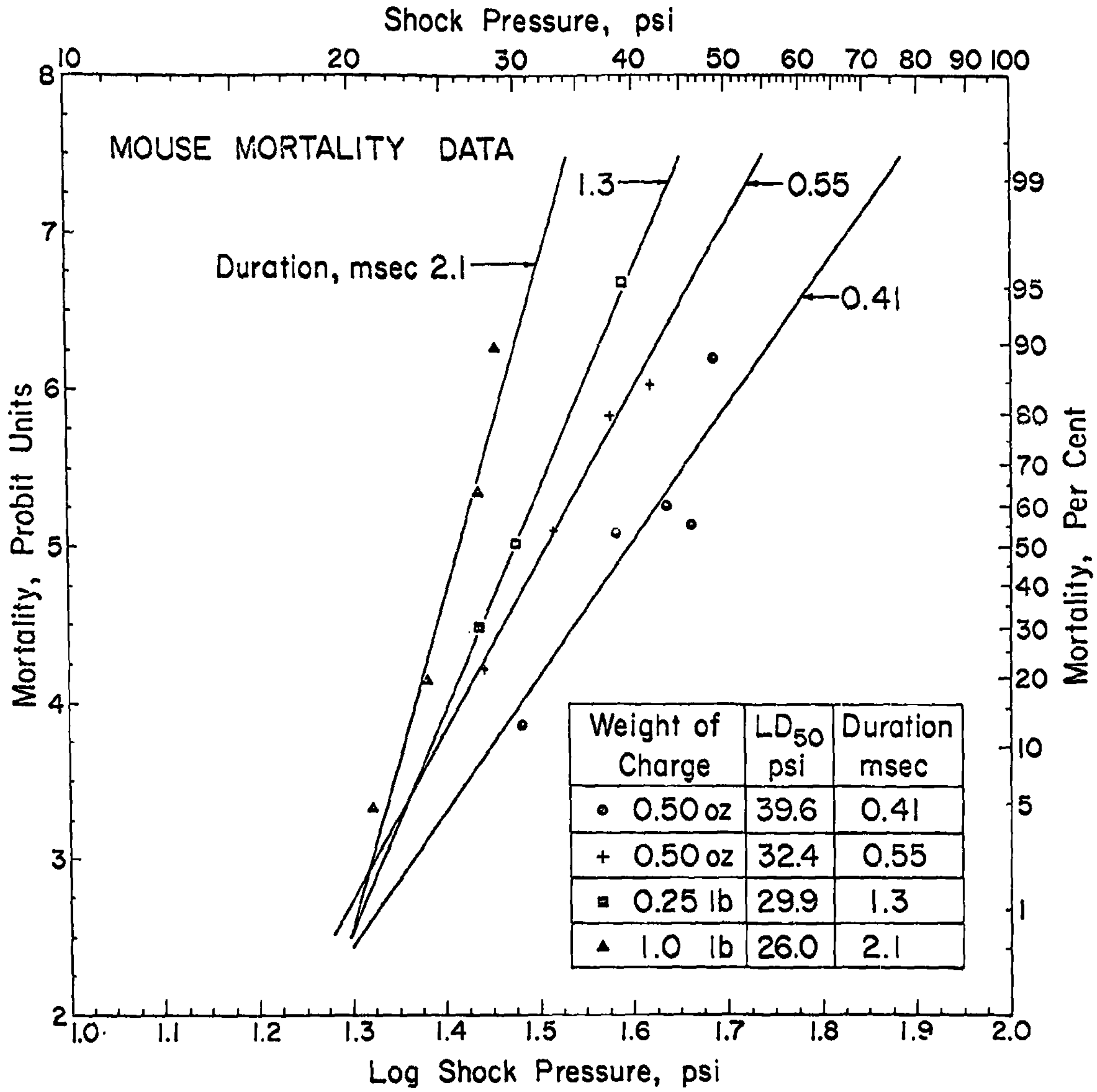
where: $y = 4.568$ (33.3-percent mortality)

$\log x = \log 63.9$ psi

$b = 19.625$ (the adjusted slope constant computed from the other four regression line equations for rabbits)

$a = 4.658 - 19.625 \times 1.806$

$a = -30.864$



Weight of Charge	LD_{50} psi	Duration msec
● 0.50 oz	39.6	0.41
+ 0.50 oz	32.4	0.55
■ 0.25 lb	29.9	1.3
▲ 1.0 lb	26.0	2.1

Figure 4

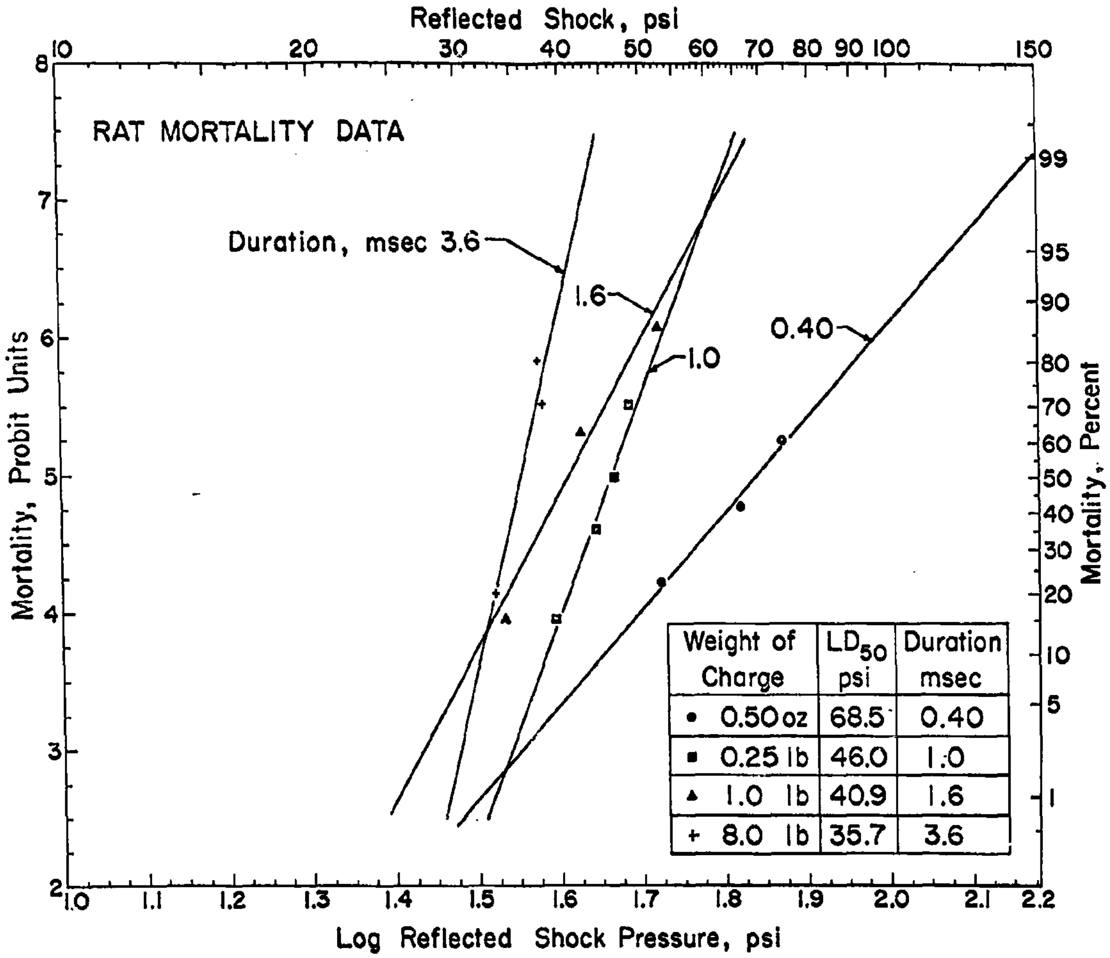

Reflected Shock, psi
10 20 30 40 50 60 70 80 90 100 150
RAT MORTALITY DATA
Duration, msec 3.6
1.6
1.0
0.40
Mortality, Probit Units
2 3 4 5 6 7 8
Mortality, Percent
1 5 10 20 30 40 50 60 70 80 90 95 99
Log Reflected Shock Pressure, psi
1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2
Weight of Charge | LD50 psi | Duration msec
• 0.50 oz | 68.5 | 0.40
▪ 0.25 lb | 46.0 | 1.0
▲ 1.0 lb | 40.9 | 1.6
+ 8.0 lb | 35.7 | 3.6

Figure 5

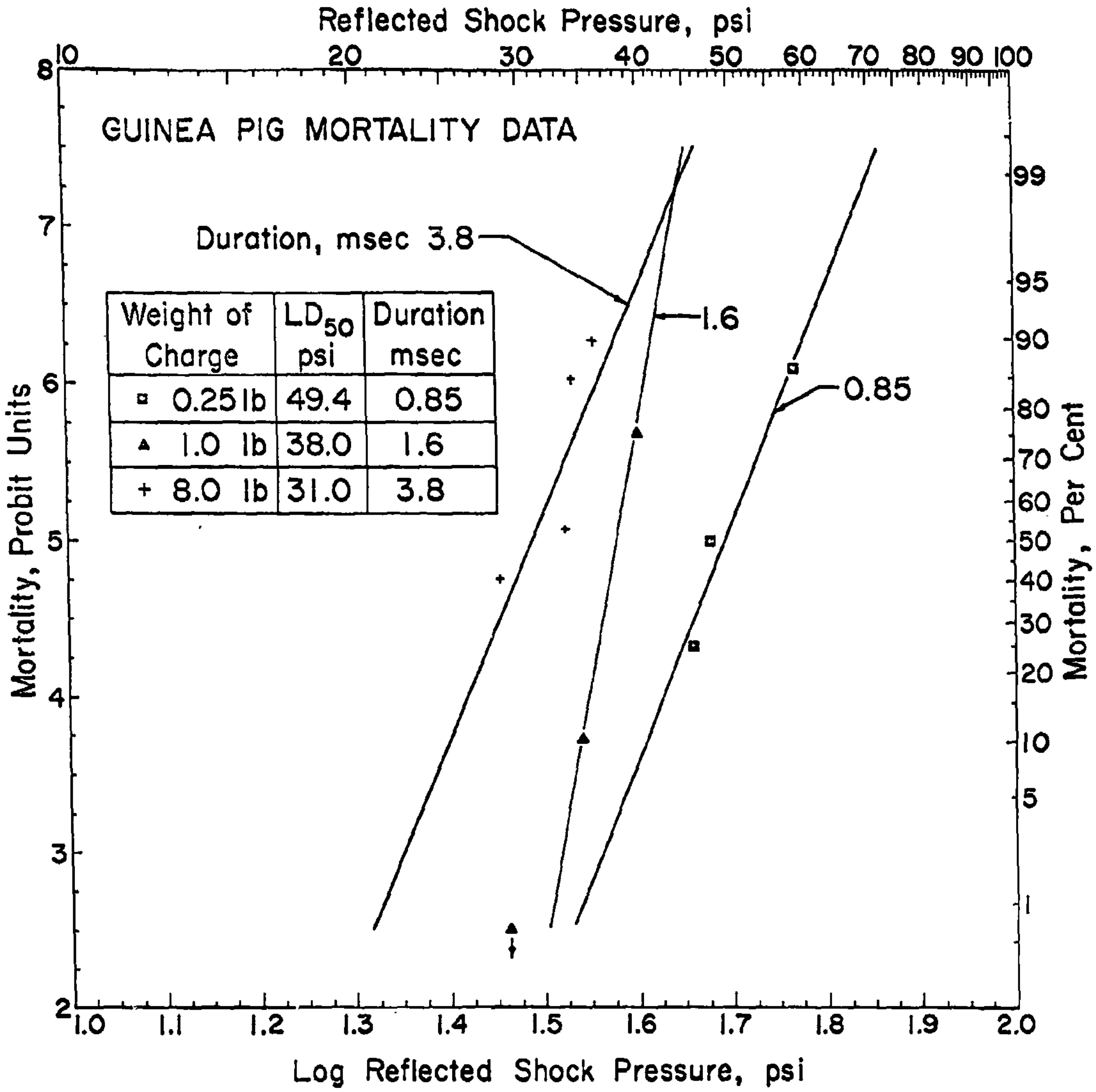
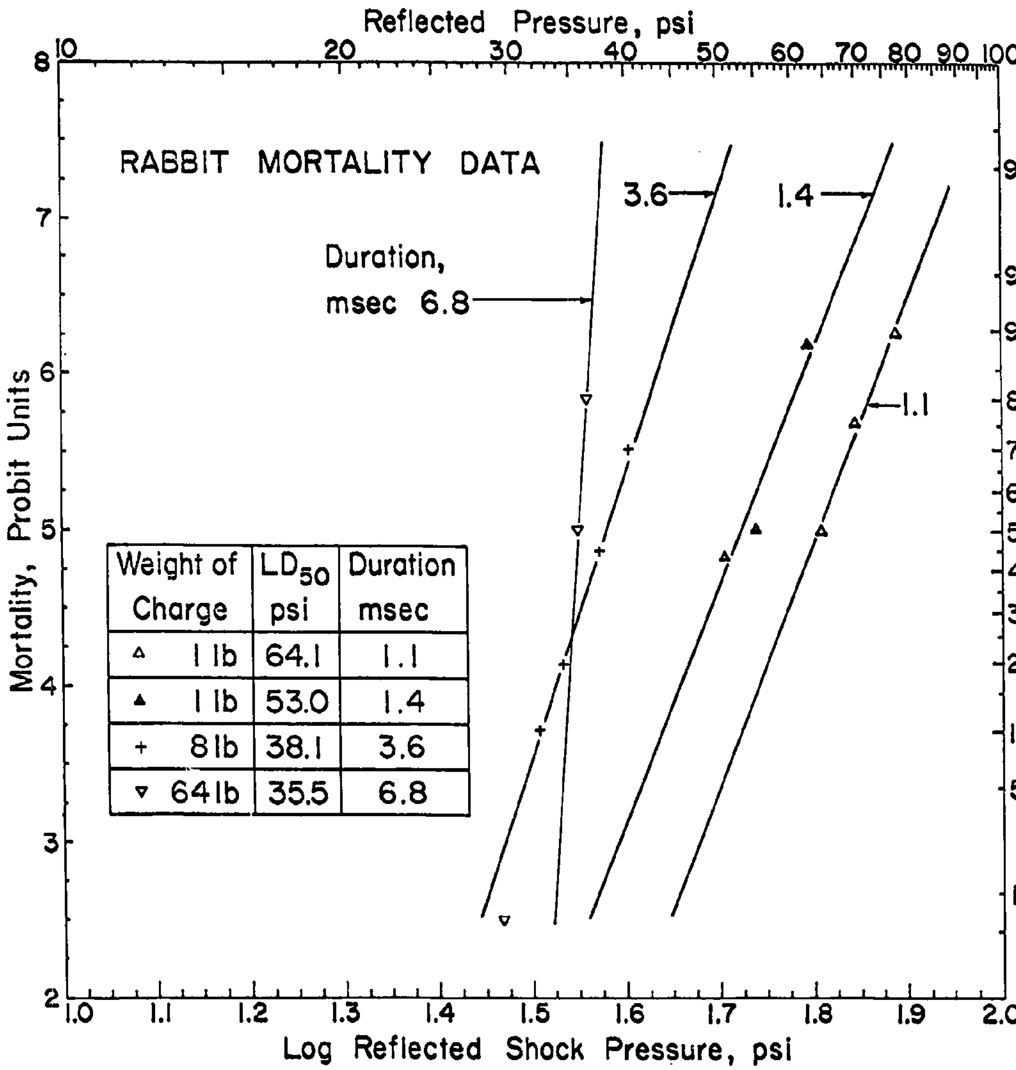

Reflected Shock Pressure, psi
10
20
30
40
50
60
70
80
90
100
GUINEA PIG MORTALITY DATA
Duration, msec 3.8
1.6
0.85
Weight of Charge
LD50 psi
Duration msec
0.25 lb 49.4 0.85
1.0 lb 38.0 1.6
+ 8.0 lb 31.0 3.8
Mortality, Probit Units
2
3
4
5
6
7
8
Mortality, Per Cent
1
5
10
20
30
40
50
60
70
80
90
95
99
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
Log Reflected Shock Pressure, psi

Figure 6



RABBIT MORTALITY DATA
Reflected Pressure, psi
Log Reflected Shock Pressure, psi
Mortality, Probit Units
Mortality, Per Cent
Duration, msec 6.8
3.6
1.4
1.1
Weight of Charge | LD50 psi | Duration msec
△ 1 lb | 64.1 | 1.1
▲ 1 lb | 53.0 | 1.4
+ 8 lb | 38.1 | 3.6
▽ 64 lb | 35.5 | 6.8

Figure 7

The derived equation was: $y = -30.864 + 19.625 \log x$. By substituting the probit of 5 (50-percent mortality) for y and solving for x, an LD50 of 67.2 psi was obtained.

The Effect of an Animal Cage on the Guinea Pig Response to the Air Blast

Table 7 compares the mortality between 20 guinea pigs exposed to air blast in cages and 20 guinea pigs without cages. Two shots were involved: both were 8 lbs at 14 ft. On the first trial there was 40- and 90-percent lethality recorded, respectively, for animals caged and not caged, with reflected shock pressures of 34.0 psi. There was 50- and 80-percent mortality for caged and non-caged animals on the second detonation in which the reflected pressure was 35.2 psi. Thus, by combining the results of the two trials, there was 45-percent mortality for guinea pigs in cages and 85 percent for non-caged animals at the mean reflected pressure of 34.6 psi.

The LD50 for non-caged guinea pigs, beneath the 8-lb charge with a mean duration of 3.8 msec, was found to be 31.0 psi (Figure 6). A calculation of the LD50 from the data in Table 7 (by the method previously described in connection with the rabbit) for caged animals of the same species was 35.2 psi. Because the mortality curves are very steep and no doubt parallel, this difference in response places the curve for the caged animals about 5 psi to the right of that for the non-caged.

The Tolerance of Small Animals to Overpressure as a Function of Duration

The results of the probit analysis on the 24-hour mortality data obtained in the present study for each of the durations are summarized in Tables 8 through 11 for the mouse, rat, guinea pig and rabbit. Included in the tables are the probit data for these species obtained with shock tube-generated reflected pressures of 6 to 8-sec[5], 400-msec[4] and 3 to 4-msec[6] durations from previous studies. The animals were mounted on the reflecting plate that closed the end of the shock tube; a geometry of exposure analogous to that employed in the study reported here. The animals tested in the shock-tube experiments were all caged.

The LD50 values for the different durations given in Tables 8 through 11 were plotted in Figure 8 for each species. As noted in Figure 8, the duration of the overpressure had a marked effect on animal tolerance. The LD50's dropped rapidly as the duration of the pressure grew and then plateaued off. At the longer durations, the tolerance of a given species to overpressure did not change importantly. It can also be pointed out in Figure 8 that the range of durations over

TABLE 7

COMPARISON OF THE MORTALITY OBTAINED WITH CAGED AND NON-CAGED GUINEA PIGS

	Pressure, psi		Duration,	Mortality (24 hrs)			
	Incident Shock	Reflected Shock	msec	Animals Caged		Animals not Caged	
	13.5	34.0	3.5	(4/10)	40%	(9/10)	90%
	14.0	35.2	3.7	(5/10)	50%	(8/10)	80%
Mean	13.8	34.6	3.6	(9/20)	45%	(17/20)	85%

1. Computed LD_{50} for caged animals 35.2 psi by adjusted slope technique, see text.
2. LD_{50} for non-caged animals 31.0 psi.
3. In both instances, the charge was 8 lb and 14 ft above the surface.

TABLE 8

THE LD_{50} PRESSURE AT VARIOUS DURATIONS FOR THE MOUSE

Pressure Source	Numbers of Animals	LD_{50}, psi	Duration of the Overpressure	Probit Equation Constants intercept, a	Probit Equation Constants slope, b
Shock Tube (Ref. 5)	115	29.8±0.8*[1]	6-8 sec	-15.856	14.148±2.334*
Shock Tube (Ref. 4)	140	30.7±0.6	400 msec	-23.636	19.255±3.426
Shock Tube (Ref. 6)	240	29.0±0.6[2]	3-4 msec	-15.052	13.718±1.536
1 lb TNT	120	26.0±0.4	2.1 msec	-24.587	20.908±3.934
0.25 lb Comp B	50	29.9±1.1	1.3 msec	-15.683	14.009±3.894
0.50 oz RDX	134	32.4±0.8	0.55 msec	-11.320	10.809±2.062
0.50 oz RDX	110	39.6±1.4	0.41 msec	-8.716	8.584±2.105

*Standard error.
[1] and [2] indicate LD_{50} at 1 hour and 2 hours, respectively; all others are LD_{50} 24-hour values.

TABLE 9

THE LD_{50} PRESSURE AT VARIOUS DURATIONS FOR THE RAT

Pressure Source	Numbers of Animals	LD50, psi	Duration of the Overpressure	Probit Equation Constants intercept, a	Probit Equation Constants slope, b
Shock Tube (Ref. 5)	55	38.6±0.6*[1]	6-8 sec	-24.882	18.827±3.169*
Shock Tube (Ref. 4)	164	36.3±0.6	400 msec	-23.826	18.485±2.596
Shock Tube (Ref. 6)	160	38.6±0.7[2]	3-4 msec	-42.510	29.954±9.354
8 lb TNT	40	35.7±0.7	3.6 msec	-36.228	26.556±7.811
1 lb TNT	80	40.9±1.4	1.6 msec	-13.122	11.234±2.365
0.25 lb Comp B	60	46.0±1.3	1.0 msec	-22.030	16.254±5.469
0.50 oz RDX	38	68.5±5.2	0.40 msec	-7.829	6.989±3.595

*Standard error.
[1] and [2] indicate LD50 at 1 hour and 2 hours, respectively; all others are LD_{50} 24-hour values.

TABLE 10

THE LD50 PRESSURE AT VARIOUS DURATIONS FOR THE GUINEA PIG

Pressure Source	Numbers of Animals	LD50, psi	Duration of the Overpressure	Probit Equation Constants intercept, a	slope, b
Shock Tube (Ref. 5)	140	36.6±0.8*[1]	6-8 sec	-25.527	19.518±3.641*
Shock Tube (Ref. 4)	96	34.5±0.6	400 msec	-28.504	21.782±3.950
Shock Tube (Ref. 6)	177	35.2±0.8[2]	3-4 msec	-15.032	12.952±1.903
8 lb TNT	82	31.0±1.1	3.8 msec	-16.456	14.393±9.198
1 lb TNT	60	38.0±0.6	1.6 msec	-48.042	33.576±9.925
0.25 lb Comp B	35	49.4±1.8	0.85 msec	-20.788	15.222±4.894

*Standard error.
[1] and[2] indicate LD50 at 1 hour and 2 hours, respectively; all others are LD_{50} 24-hour values.

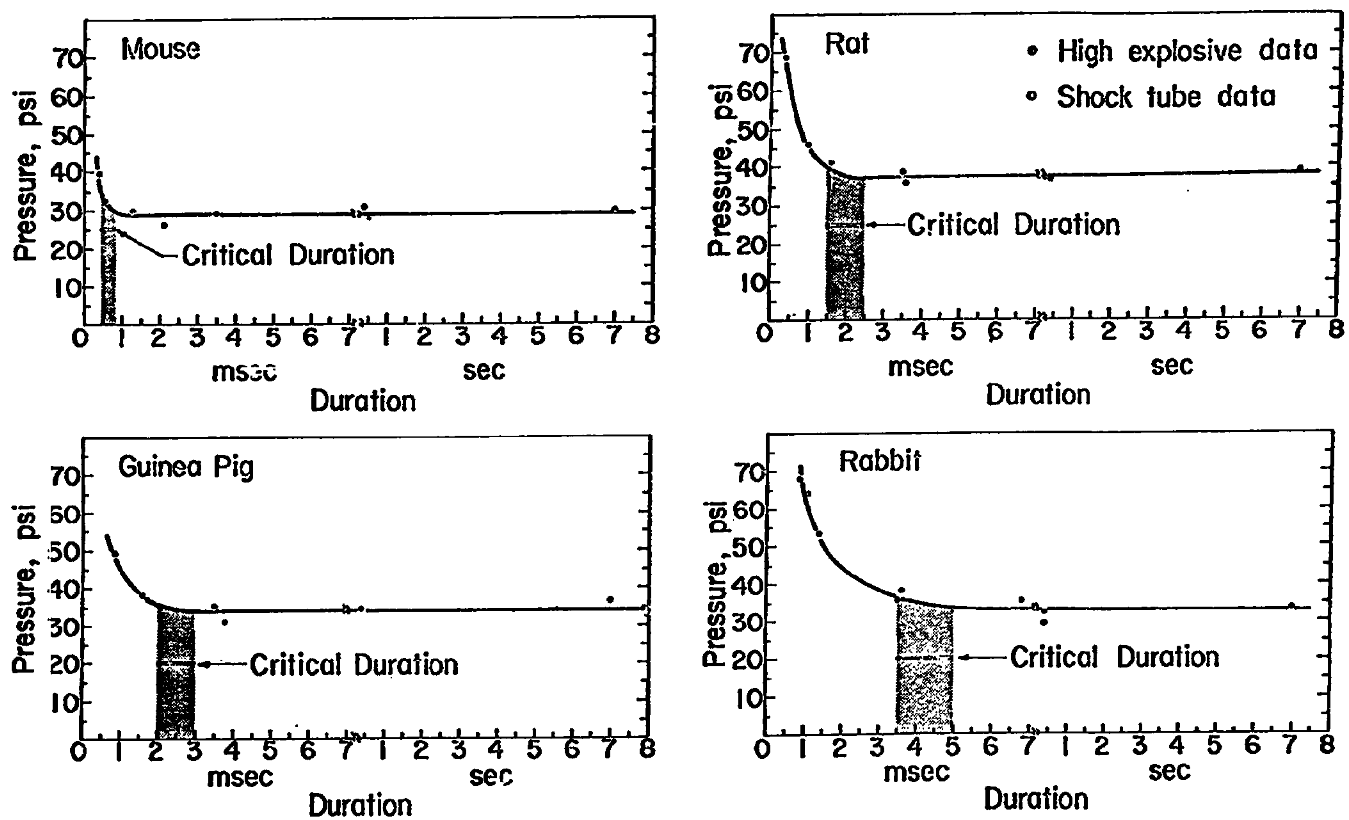
TABLE 11

THE LD_{50} PRESSURE AT VARIOUS DURATIONS FOR THE RABBIT

Pressure Source	Numbers of Animals	LD50, psi	Duration of the Overpressure	Probit Equation Constants intercept, a	Probit Equation Constants slope, b
Shock Tube (Ref. 5)	145	33.6±0.8*[1]	6-8 sec	-25.703	20.117±5.664*
Shock Tube (Ref. 4)	104	29.6±0.9	400 msec	-13.630	12.666±2.066
64 lb TNT	36	35.5±1.9	6.8 msec	-129.803	86.957±56.443
Shock Tube (Ref. 6)	84	35.6±0.8[2]	3-4 msec	-24.354	18.924±3.909
8 lb TNT	70	38.1±0.8	3.6 msec	-23.882	18.268±6.100
1 lb TNT	31	53.0±2.0	1.4 msec	-21.149	15.164±6.940
1 lb TNT	18	64.1±5.5	1.1 msec	-23.291	15.659±10.185
0.25 lb Comp B	9	67.2	0.90 msec	--	--

*Standard error.
[1] and [2] indicate LD50 at 1 hour and 2 hours, respectively; all others are LD_{50} 24-hour values.

LD$_{50}$ Curves for Small Animals Obtained with Sharp-rising Pressures of Various Durations



HE Data

Figure 8

which the tolerance to overpressure (LD_{50}) began to climb was different for each of the four species and appeared to be related to their size. For instance, the rabbit curve began to rise over the 3.5- to 5-msec range; that for the mouse, over the 0.4- to 0.8-msec region. The guinea pig and rat, respectively, rose over the 2- to 3-msec and 1.5- to 2.5-msec durations. The duration of the pressures over which the curves initially started to ascend has been termed the "critical duration"[6]. Thus, for pulse durations shorter than the critical duration, both the peak pressure and the duration are definitive for lethality. For overpressures longer than the critical duration, it is only the magnitude of the pressure that is significant for lethality.

DISCUSSION

The results of this investigation, with those from previous shock-tube studies undertaken at this laboratory[4, 5, 6], have fairly well defined the response of mice, rats, guinea pigs and rabbits to single-pulse, sharp-rising overpressures as a function of duration. The results showed that the duration of the positive phase had a marked effect on the animals' resistance to air blast — especially at the shorter durations. The results provided extensive tolerance data that will receive further analytical treatment aimed at an understanding of the mechanism involved in air-blast injury. Moreover, the data furnished base line information on which the results of future experiments dealing with protection against blast will be evaluated.

At the present time, one cannot relate biological response to any one physical parameter of the blast wave, except possibly for classical pulses of very long duration. Previous investigators[8, 9] also have pointed out that biological response could not be directly correlated with either the impulse (pressure-time integral) or the maximal pressure. Thus, with small charges (short durations), both the maximal pressure and its duration must be specified in defining the dose; whereas with large charges (long durations), the maximal pressure appears to be the physical component associated with animal response. A mathematical model of the fluid-mechanical behavior of the thoracic-abdominal structures in connection with pressure-time measurements taken in the animals' thorax during exposure to blast may help in establishing parameters of significance[10].

It should be emphasized here that papers have been published to show that animal tolerance rises when the overpressure is applied in two distinct shocks separated by a short time-interval[5, 11, 12, 13]. Consequently, the tolerance values (LD_{50}) reported herein can only apply to pressure pulses that rise in a nearly instantantous manner.

In these studies, the animals were exposed to the air blasts without cages in order to make the data directly comparable to that for larger species which are usually held in place by methods other than caging. The results of the tests, which compared guinea pig lethality with caged and non-caged animals, revealed that some protection was afforded against the shock wave by the particular type of caging employed. This could explain why the shock tube LD_{50} values obtained with caged animals tended to be slightly higher than those compiled with high explosives at durations beyond the critical range. Be that as it may, properly designed cages minimize displacement of animals by the blast, and this displacement, under certain conditions of exposure, could introduce more uncertainties than the protection afforded by caging.

As previously mentioned, the critical duration appears to vary with species size. Experiments are now in progress to determine the influence the pressure-duration relationship has on lethality, as well as the "critical duration", for several large mammalian species. It is hoped that the "critical duration" may aid in the extrapolation of these data to the 70-kg animal.

The main objective of this study was to determine the LD_{50} pressures for different durations. In most instances, a sufficient number of animals was used to get reliable LD_{50} values. On the other hand, the number of data points associated with each of the mortality curves did not permit calculation of slope constants with any high degree of confidence. The apparent parallelism of the slopes, however, does suggest that there may be a single slope constant common to all dose-mortality curves for air blast. In other words, an identical slope might be associated with all probit-mortality curves — regardless of species and for any pressure-time pattern. Unfortunately, any conclusions, in regard to a constant-slope hypothesis, have to await further study.

SUMMARY

1. A total of 993 small animals were employed in this study, of which there were 414 mice, 218 rats, 197 guinea pigs and 164 rabbits.

2. The animals were exposed to graded levels of overpressures of different durations by mounting them prone on a concrete pad above which high-explosive charges of different weights were detonated at various heights.

3. In all, 185 high-explosive charges were used. The weights were 64, 8, 1 and 0.25 lbs and 0.50 oz.

4. Pressure-time measurements were taken with pencil-type and shock-tube piezo-electric gauges mounted on the concrete pad directly beneath the explosive charge.

5. The probit analysis was applied to the mortality data. The LD50 24-hour reflected pressures computed for each of the durations studied were as follows:

Weight of Charge	LD$_{50}$ Reflected Pressure, psi			
	Mouse	Rat	Guinea Pig	Rabbit
0.50 oz	39.6*(0.41)**	68.5(0.40)	--	--
	32.4(0.55)	--	--	--
0.25 lb	29.9(1.3)	46.0(1.0)	49.4(0.85)	67.8(0.90
1 lb	26.0(2.1)	40.9(1.6)	38.0(1.6)	64.1(1.1)
	--	--	--	53.0(1.4)
8 lb	--	35.7(3.6)	31.0(3.8)	38.1(3.6)
64 lb	--	--	--	35.5(6.8)

*Incident shock pressure, in this instance.
**The numbers in parentheses are the durations in msec.

6. By combining the results of this study with those from previous shock-tube studies, it was possible to relate the tolerance of four small-animal species to air blast as a function of pressure duration.

7. The relation between biologic response and the physical parameters of the blast wave were briefly discussed.

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